

METHOD AND APPARATUS FOR FABRICATING A CONFORMAL
THIN FILM ON A SUBSTRATE

TECHNICAL FIELD OF THE INVENTION

The present invention generally relates to film deposition, and more particularly to a method and apparatus for fabricating a conformal thin film on a substrate.

BACKGROUND OF THE INVENTION

Atomic layer deposition (ALD), also known as sequential pulsed chemical vapor deposition (SP-CVD), atomic layer epitaxy (ALE) and pulsed nucleation layer 5 (PNL) deposition, has gained acceptance as a technique for depositing thin and continuous layers of metals and dielectrics with high conformality. In an ALD process, a substrate is alternately dosed with a precursor and one or more reactant gases so that reactions are limited to 10 the surface of a substrate. Uniform adsorption of precursors on the wafer surface during the ALD process produces highly conformal layers at both microscopic feature length scales and macroscopic substrate length scales, and achieves a high density of nucleation sites. 15 These attributes result in the deposition of spatially uniform, conformal, dense and continuous thin films.

Although ALD techniques support deposition of conformal thin layers, a drawback of the technique is the low average deposition rate, which is related to the need 20 to repeat several cycles having finite durations. For example, the repeated cycle of precursor and reactant adsorption and the intervening chamber purges is time consuming, which results in reduced throughput relative to conventional deposition techniques. Specifically, an 25 ALD sequence includes at least two purge pulses and these purge pulses are typically the most time consuming portion of the ALD sequence. Therefore, improvements in ALD equipment have focused on techniques to decrease the time needed to complete a purge pulse.

30 The most logical solution to decreasing the duration of the purge pulse is to flow the purge gas at higher

speeds through the reactor, which may be achieved by increasing the flow rate of the purge gas. Typical flow rates used in the industry are several standard liters per minute (SLM) (e.g., approximately 2.5 SLM) at pressures of between approximately 0.2 and approximately 20 Torr. These flow rates lead to substantially higher gas flow speeds than obtained in conventional CVD processes.

One of the effects of increasing purge gas flow speed is the occurrence of turbulence in the gas injector. Typically, the turbulence occurs in an expansion zone of a gas injector near an inlet used to supply the purge gas. Turbulence in the expansion zone may cause the flow pattern of the purge gas across a conventional diffuser plate to be altered. Specifically, the fraction of the total flow passing through the openings in the diffuser plate located near the turbulent zone decreases significantly. The decrease in gas flow through openings near the turbulent zone when compared to the gas flow through openings located away from the turbulent zone may create an uneven distribution of precursor during a doping, which ultimately forms a non-uniform film on a substrate. Additionally, recirculation of gas in the expansion zone caused by the turbulence leads to inefficient purging of the precursors from the expansion zone, which may cause gas phase reactions that form a powder in the expansion zone.

SUMMARY OF THE INVENTION

In accordance with the present invention, the disadvantages and problems associated with fabricating conformal thin films on a substrate have been 5 substantially reduced or eliminated. In a particular embodiment, an apparatus for fabricating conformal thin films on a substrate is disclosed that include a diffuser plate having a protrusion that reduces turbulence in an expansion volume associated with a gas injector.

10 In accordance with one embodiment of the present invention, a method for fabricating conformal thin films on a substrate includes introducing a gas from a gas inlet into an expansion volume associated with an atomic layer deposition (ALD) system. The gas is flowed through 15 a diffuser plate adjacent to the expansion volume and a reaction chamber. The diffuser plate includes a protrusion located opposite the gas inlet, which reduces turbulence in the expansion volume.

20 In accordance with another embodiment of the present invention, an apparatus for fabricating conformal thin films on a substrate includes a reaction chamber and a gas injector located adjacent to the reaction chamber. The gas injector includes an expansion volume and a gas inlet for introducing a gas into the expansion volume. A 25 diffuser plate is located adjacent to the expansion volume and the reaction chamber. A protrusion that reduces turbulence in the expansion volume is located adjacent to the diffuser plate and opposite the gas inlet.

30 In accordance with a further embodiment of the present invention, an apparatus for fabricating conformal

thin films on a substrate includes a reaction chamber and a gas injector located adjacent to the reaction chamber. The gas injector includes an expansion volume and a gas inlet for introducing an inert gas into the expansion 5 volume. A diffuser plate located adjacent to the expansion volume and the reaction chamber includes a bevel that is located opposite the gas inlet, and reduces turbulence and gas phase reactions in the expansion volume.

10 Important technical advantages of certain embodiments of the present invention include a diffuser plate that suppresses turbulence in a gas injector over a wide range of flow rates. The diffuser plate includes a protrusion located opposite a gas inlet of a gas 15 injector. The protrusion prevents gas flowing from the gas inlet from bouncing off the surface of the diffuser plate and recirculating in an area around the gas inlet. The protrusion, therefore, facilitates laminar gas flow in an expansion volume of a gas injector associated with 20 an ALD system.

Another important technical advantage of certain embodiments of the present invention includes a diffuser plate that increases throughput of an ALD system. The diffuser plate includes a protrusion that facilitates 25 laminar gas flow throughout an expansion volume of a gas injector. The laminar gas flow allows the gas during a purge pulse of an ALD process to remove residual precursor from the expansion volume. By more effectively removing the precursor, gas phase reactions during a 30 subsequent purge pulse may be reduced or even eliminated, thus decreasing the frequency of cleaning processes.

A further important technical advantage of certain embodiments of the present invention includes a diffuser plate that uniformly distributes a precursor in a reaction chamber. During a doping, a precursor combined with a gas may be flowed through the diffuser plate. A protrusion on the diffuser plate facilitates a laminar gas flow within an expansion volume. Because gas/precursor mixture flows in a laminar manner within the expansion volume, the gas/precursor mixture flows more uniformly through openings in the diffuser plate. The uniform flow of the mixture provides for an improved distribution of precursor over a substrate in the reaction chamber and ultimately allows a substantially uniform film to be formed on the substrate.

All, some, or none of these technical advantages may be present in various embodiments of the present invention. Other technical advantages will be readily apparent to one skilled in the art from the following figures, descriptions, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete and thorough understanding of the present embodiments and advantages thereof may be acquired by referring to the following description taken 5 in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIGURE 1 illustrates an atomic layer deposition (ALD) system for forming a conformal thin film on a 10 substrate according to teachings of the present invention;

FIGURES 2A and 2B illustrate flow patterns in a gas injector at different flow rates using a conventional diffuser plate;

15 FIGURES 3A and 3B illustrate flow patterns over a substrate at different flow rates using a conventional diffuser plate;

FIGURE 4 illustrates an example embodiment of a gas 20 injector associated with an ALD system according to teachings of the present invention;

FIGURE 5 illustrates another example embodiment of a gas injector associated with an ALD system according to teachings of the present invention;

FIGURES 6a and 6b respectively illustrate a top view 25 and a bottom view of an example embodiment of a diffuser plate including protrusions formed on a top surface according to teachings of the present invention; and

FIGURE 7 illustrates a gas injector flow pattern using a beveled diffuser plate according to teachings of 30 the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention and their advantages are best understood by reference to FIGURES 1 through 7, where like numbers are used to 5 indicate like and corresponding parts.

The conceptual groundwork for the present invention involves an atomic layer deposition (ALD) process to create highly conformal thin films. In an ALD process, individual precursors are pulsed onto the surface of a 10 substrate contained in a reaction chamber, without mixing the precursors in the gas phase. Each precursor reacts with the surface of the substrate to form an atomic layer in such a way that only one layer forms at a time. The introduction of the precursor into the reaction chamber 15 may be known as a doping. In between doping pulses, the reaction chamber may be purged by flowing a gas over the substrate. The time needed to complete the doping and purge pulses may depend on the flow rate of the precursor or the purge gas. In conventional ALD systems, the 20 precursor or purge gas flows from a gas injector, through a diffuser and into the reaction chamber. The diffuser may include a flat surface having multiple openings to allow the precursor or purge gas to flow into the reaction chamber. If the flow rate of the purge gas 25 during the purge pulse is above a specific level, turbulence may occur near the gas inlet in the injector. The present invention provides a protrusion associated with the diffuser that reduces and even eliminates turbulence in the gas injector. The protrusion may be 30 located opposite the gas inlet such that the purge gas

flows over the protrusion and through the openings in the diffuser in a more uniform manner.

FIGURE 1 illustrates atomic layer deposition (ALD) system 10 for forming a conformal thin film on a substrate. In the illustrated embodiment, ALD system 10 includes diffuser plate 12, gas lines 14a and 14b (generally referred to as gas lines 14), gas injector 16, reaction chamber 18 and outlet 20. During a purge pulse, a gas may flow through one or both of gas lines 14a and 14b from gas reservoirs. The gas then flows through diffuser plate 12 included in gas injector 16. A protrusion may be located opposite the gas inlet. The protrusion functions to direct the gas within gas injector 16 such that the gas flows in a laminar manner over a wide range of flow rates.

ALD system 10 may include one or more gas reservoirs (not expressly shown) connected to gas injector 16 by gas lines 14. In one embodiment, the reservoirs may contain an inert gas that is used to remove precursor from gas injector 16 during a purge pulse and/or that is combined with a precursor during a doping. In another embodiment, the reservoirs may contain a precursor used during a doping pulse. Gas lines 14 may feed the gas into gas injector 16. In one embodiment, gas lines 14 may be formed of stainless steel and have a diameter of approximate one-quarter ($\frac{1}{4}$) inch. Although the illustrated embodiment shows a particular number of reservoirs and associated gas lines, ALD system 10 may include a single reservoir and gas line or more than two reservoirs and their corresponding gas lines.

Reaction chamber 18 may contain substrate holder 19. In one embodiment, a substrate placed in substrate holder 19 may be a p-type or n-type silicon substrate. In other embodiments, the substrate may be formed from gallium arsenide or any other suitable material that may be used as a substrate on which one or more layers of material may be deposited. The one or more layers deposited by ALD system 10 may form films used to fabricate conformal barriers, high-k dielectrics, gate dielectrics, tunnel dielectrics and barrier layers for semiconductor devices.

ALD films are also thermally stable and substantially uniform, which makes them attractive for optical applications. Another potential application for ALD is the deposition of AlO_x as a gap layer for thin film heads, such as heads for recording densities of 50 Gb/in² and beyond that require very thin and conformal gap layers. Additionally, ALD thin films may be used to form structures with high aspect ratios, such as MicroElectroMechanical (MEM) structures.

The thin film may be formed on a substrate by alternately flowing one or more precursors combined with an inert gas (e.g., a doping pulse) and the inert gas (e.g., a purge pulse) through reaction chamber 18. The precursor may react with the surface of the substrate to form a single layer of film. The doping and purge pulses may be repeated until a thin film having the desired thickness is formed on the substrate. During the pulses, the gas and precursor may be removed from reaction chamber 18 through outlet 20 by a pump (not expressly shown).

During the purge pulse, the gas from the reservoirs expands into an area contained in gas injector 16. In conventional ALD systems, if the flow rate of the gas is high enough (e.g., greater than approximately 500 sccm), 5 turbulence may occur due to the flat surface of a diffuser plate located opposite the gas inlet of gas injector 16. The turbulence prevents the gas in a purge pulse from completely clearing the precursor from gas injector 16 because the precursor may be trapped in the 10 turbulence, which may lead to gas phase reactions during subsequent pulses that form a powder in gas injector 16. As described below in reference to FIGURE 2B, the 15 turbulence may decrease the total flow of gas passing through openings in the diffuser plate located near the turbulent zone.

In the present invention, the expansion volume located in gas injector 16 may include a protrusion located opposite the gas inlet. In one embodiment, the protrusion may be integral to diffuser plate 12 located 20 between gas injector 16 and reaction chamber 18. In another embodiment, the protrusion may be separate from diffuser plate 12 and mounted to one of the walls associated with gas injector 16.

In one embodiment, the protrusion may be beveled and 25 the surfaces forming the bevel may have similar or different slopes. In other embodiments, the protrusion may include several sloped segments having different slopes or a surface with a smoothly varying slope. The protrusion functions to reduce and even eliminate 30 turbulence at typical gas flow rates (e.g., approximately 2500 sccm and greater) for an ALD process by directing

the flow of the gas through gas injector 16 such that the flow is uniform through each of the openings in the diffuser plate. Additionally, the protrusion may prevent gas phase reactions from occurring in gas injector 16
5 because the purge pulse more effectively removes the precursor from gas injector 16.

FIGURES 2A and 2B illustrate flow patterns inside of a gas injector at different flow rates using a conventional diffuser plate. Specifically, FIGURE 2A
10 illustrates the flow pattern of a gas inside gas injector 30 at a flow rate of approximately 100 sccm. A gas may be introduced into gas injector 30 through gas inlet 32. At the low flow rate, the gas flows substantially uniformly over diffuser plate 34. As shown, no
15 turbulence is present due to the low flow rate and the gas may flow through openings 36 in a uniform manner.

However, as illustrated by FIGURE 2B, at a flow rate of approximately 500 sccm (e.g., a rate approximately five times greater than the rate illustrated in FIGURE
20 2A), turbulent zones may occur near gas inlet 32. The turbulence causes a drop in pressure, which causes the flow through openings 36 located opposite gas inlet 32 to be lower than openings 36 located away from gas inlet 32. In some cases, if the pressure in the gas injector near
25 the turbulent zones is lower than the pressure in the reaction chamber, the gas may actually be sucked from the reaction chamber into the gas injector. The different flow through openings 36 may cause an uneven distribution of the precursor during the doping pulse. Additionally,
30 the recirculation in the turbulent zones may lead to inefficient purging of the precursor in gas injector 30,

which may cause gas phase reactions that produce powder in gas injector 30. The powder may damage the substrate contained in the reaction chamber and create a need to clean the ALD system more often.

FIGURES 3A and 3B illustrate flow patterns over a substrate at different flow rates using a conventional diffuser plate. Specifically, FIGURE 3A shows the flow pattern of a gas above a substrate (not expressly shown) at a flow rate of approximately 133 sccm as calculated by a commercially available computational flow dynamics software (e.g., software developed and sold by CFDRC corporation of Huntsville, Alabama). As illustrated, the gas flows substantially uniformly from gas injector 40 over the substrate to outlet 42. FIGURE 3B shows the flow pattern of the gas at a flow rate of approximately 1333 sccm (e.g., a rate approximately ten times greater than the flow rate illustrated in FIGURE 3A). As shown, the gas flow over the substrate is substantially different at the higher flow rate, especially in the region directly opposite the gas inlet (not expressly shown) in gas injector 40. As described above in reference to FIGURE 2B, a conventional diffuser plate may induce turbulence in the region of gas injector 40 near the gas inlet. As shown in FIGURE 3B, the turbulence may reduce the amount of gas flowing through the openings in the diffuser plate that are located opposite the gas inlet. The difference in the flow pattern through the openings in the diffuser plate may cause non-uniform distribution of the precursor over the substrate.

FIGURE 4 illustrates an example embodiment of a diffuser plate including a protrusion located opposite a

gas inlet in a gas injector associated with an ALD system. Gas line 14 may include fast valving system 51 located near gas inlet 53 of gas injector 16. Fast valving system 51 may include several subcomponents, such 5 as mass flow controllers and on/off valves to control the flow versus time profiles of the dosing and purge pulses. A gas may flow through fast valving system 51 into expansion volume 52 via gas inlet 53. The flow of gas from expansion volume 52 to reaction chamber 18 may be 10 restricted by diffuser plate 12. In one embodiment, diffuser plate 12 may be a metal plate including at least one opening 56. The number, size and position of openings 56 may be selected to obtain uniform precursor flow in reaction chamber 18 during a doping pulse and 15 uniform gas flow during a purge pulse. Diffuser plate 12 may further be disposable since prolonged use may lead to deposition of the precursor in openings 56 and subsequent alteration of flow characteristics over time.

In the illustrated embodiment, diffuser plate 12 20 includes protrusion 58 located opposite gas inlet 53. Protrusion 58 may direct the gas flowing into expansion volume 52 such that the gas flows uniformly through each of openings 56 into reaction chamber 18 through openings 56. The height of protrusion 58 may scale with the size 25 of gas inlet 53 and a desired operation range for the flow rate. In general, the size of gas inlet 53 and the flow rate may depend on the size of the substrate, as larger amounts of precursor may be used for larger substrates. In one embodiment, the substrate may have a 30 diameter of approximately 150 millimeters and protrusion 58 may have a height between approximately three

millimeters (3 mm) and approximately eight millimeters (8 mm).

Protrusion 58 may include surfaces 57 and 59 that form a bevel. In the illustrated embodiment, surfaces 57 and 59 may have approximately the same length and slope. In other embodiments, one of surfaces 57 and 59 may have a larger slope and/or length than the other surface. In a further embodiment, protrusion 58 may be formed in the shape of an inverted "U" such that the surface of protrusion 58 has a smoothly varying slope. In yet another embodiment, protrusion 58 may include more than two sloped segments where the sloped segments have the same or different slopes and lengths.

Surface 57 may form a first angle (Φ_1) with respect to the surface of diffuser plate 12 and surface 59 may form a second angle (Φ_2) with respect to the surface of diffuser plate 12. In one embodiment, the first and second angles (Φ_1 and Φ_2) may be between approximately thirty degrees (30°) and approximately sixty degrees (60°). The first and second angles (Φ_1 and Φ_2) may be approximately equal or one of the angles may be greater or less than the other angle.

Protrusion 58 functions to direct the gas flow toward openings 56 in diffuser plate 12 such that the amount of gas flowing through each of openings 56 is approximately equal. Protrusion 58 may further function to eliminate turbulence in expansion volume 52 by preventing the gas from bouncing off of the surface of diffuser plate 12 towards gas inlet 53, which further prevents recirculation from occurring near gas inlet 53. By eliminating recirculation of the gas in expansion

volume 52, the precursor may be more efficiently purged from expansion volume 52 during the purge pulse, which reduces the possibility of gas phase reactions that may form a powder in expansion volume 52 after prolonged use 5 of ALD system 10.

In another embodiment, protrusion 58 may be separate from diffuser plate 12. Protrusion 58 may be mounted in expansion volume 52 such that protrusion 58 is located opposite gas inlet 53. For example, protrusion 58 may be 10 located on a post mounted to one of the walls of expansion volume 52. The post may have a width or diameter less than or equal to the base of protrusion 58. Additionally, the post may have a shape similar to that 15 of protrusion 58 in order to further aid the flow of gas in expansion volume 52.

In a further embodiment, a wall protrusion, similar to protrusion 58 located on diffuser plate 12, may be formed on at least one of the walls forming expansion volume 52. The wall protrusion may be formed on at least 20 one of the walls in order to provide a more uniform gas flow through expansion volume 52 and to further reduce turbulence at higher flow rates. The wall protrusion may have one or more surfaces. In one embodiment, the 25 surfaces may have approximately the same lengths and/or slopes. In other embodiments, the surfaces of the wall protrusion may have different lengths and/or slopes. In further embodiments, the surface of the wall protrusions may form an inverted "U".

FIGURE 5 illustrates another example embodiment of a 30 diffuser plate including a protrusion located opposite a gas inlet in a gas injector associated with an ALD

system. In the illustrated embodiment, gas inlet 53 may be located at the top of expansion volume 52, rather than the center as illustrated in FIGURE 4. Diffuser plate 12 may include protrusion 60 that functions to direct the 5 gas flow toward the bottom of expansion volume 52. In another embodiment, protrusion 60 may be separate from diffuser plate 12 and formed on the wall of expansion volume 52. Protrusion 60 may form an angle (Φ) with respect to the surface of diffuser plate 12 of 10 approximately thirty degrees (30°) to approximately sixty degrees (60°). Protrusion 60 may allow the gas flow to be evenly distributed through openings 56 such that a precursor is evenly distributed in reaction chamber 18.

Although protrusion 60 is illustrated as having a 15 single surface adjacent to a wall of expansion volume 52, protrusion 60 may also have multiple surfaces. For example, gas inlet 53 may be located in a slightly asymmetrical position relative to the walls of expansion volume 52. Protrusion 60 may include at least two 20 surfaces, where the surface extending toward the larger portion of expansion volume 52 may have a greater length than the surface extending toward the smaller area of expansion volume 52.

FIGURES 6a and 6b respectively illustrate a top view 25 and a bottom view of an example embodiment of diffuser plate 12 including protrusions 58a and 58b. As illustrated in FIGURE 1, ALD system 10 may include gas lines 14a and 14b. Each of gas lines 14a and 14b may include a corresponding gas inlet and when diffuser plate 30 12 is used in ALD system 10, protrusions 58a and 58b may be respectively located opposite the gas inlets for gas

lines 14a and 14b. In this example, protrusions 58a and 58b may respectively prevent turbulence from forming near the gas inlets associated with gas lines 14a and 14b. In other embodiments, diffuser plate 12 may include any 5 suitable number of protrusions 58 such that at least one protrusion is located opposite each of the gas inlets associated with the expansion volume of a gas injector.

As shown in FIGURE 6a, diffuser plate 12 includes two rows of openings 56 formed on a front surface. As 10 described above in reference to protrusions 58a and 58b, the two rows of openings 56 may correspond to the number of gas inlets associated with the expansion volume. In other embodiments, diffuser plate 12 may include one row or greater than two rows of openings 56 where the number 15 of rows depends on the number of gas inlets associated with the expansion volume of the gas injector.

As shown in FIGURE 6b, diffuser plate 12 may include chamber openings 54 formed on a back surface. Chamber openings 54 may be located adjacent to reaction chamber 18 when diffuser plate 12 is included in ALD system 10 illustrated in FIGURE 1. In order to ensure that the precursor and gas enters reaction chamber 18 through each one of openings 56 at the same location, openings 56 may be interleaved in diffuser plate 12 to form a single row 25 of chamber openings 54. In the illustrated embodiment, openings 56 may be formed in diffuser plate 12 at a forty-five degree angle with respect to the normal of the surface of diffuser plate 12. In other embodiments, openings 56 may be formed in diffuser plate 12 at a 30 suitable angle such that each of openings 56 forms a single corresponding chamber opening 54. In a further

embodiment, the number of rows of chamber openings 54 formed on a back surface of diffuser plate 12 may be equal to the number of rows of openings 56 formed on a front surface of diffuser plate 12.

5 FIGURE 7 illustrates a gas injector flow pattern using a beveled diffuser plate. In the illustrated embodiment, the flow rate is approximately 8000 sccm. As shown, protrusion 58 may facilitate a laminar gas flow at a flow rate approximately sixteen (16) times greater than
10 the flow rate at which the conventional diffuser plate illustrated in FIGURE 2B shows significant turbulence. The gas, therefore, may be evenly distributed through each of openings 56 and the precursor distribution in reaction chamber 18 may be improved.

15 Although the present invention has been described with respect to a specific preferred embodiment thereof, various changes and modifications may be suggested to one skilled in the art and it is intended that the present invention encompass such changes and modifications fall
20 within the scope of the appended claims.